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Cite as: AIP Conference Proceedings **2303**, 160009 (2020); https://doi.org/10.1063/5.0028950
Published Online: 11 December 2020

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Forecasting of Power Production of a Parabolic Trough Plant Using EO and NWP Data

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Abstract. TSK Flagsol Engineering GmbH through a cooperation with the DLR (the German Aerospace Center) and sponsored by the European Space Agency (ESA) has developed a weather and energy production forecasting system called CSP-FoSyS for the operation of CSP power plants. CSP-FoSyS is both a meteorological and an electrical and thermal power forecast system based on satellite based nowcasting, numerical weather prediction model and cloud cameras based forecasts. The system integrates these several forecasting methods through a concept called "the merger", providing forecasts for the use in concentrated solar power (CSP) plants.

CSF FOSYS OVERVIEW

CSP-FoSyS has five sub-systems as shown in FIGURE 1. The system uses satellite satellites' earth observation data, numerical weather predictions, cloud cameras, local measurements, and the power plant's data as inputs in order to provide the user with both meteorological and power forecasts. The system is also used for day-ahead and intraday markets as well as for ongoing operation optimization of the power plant.

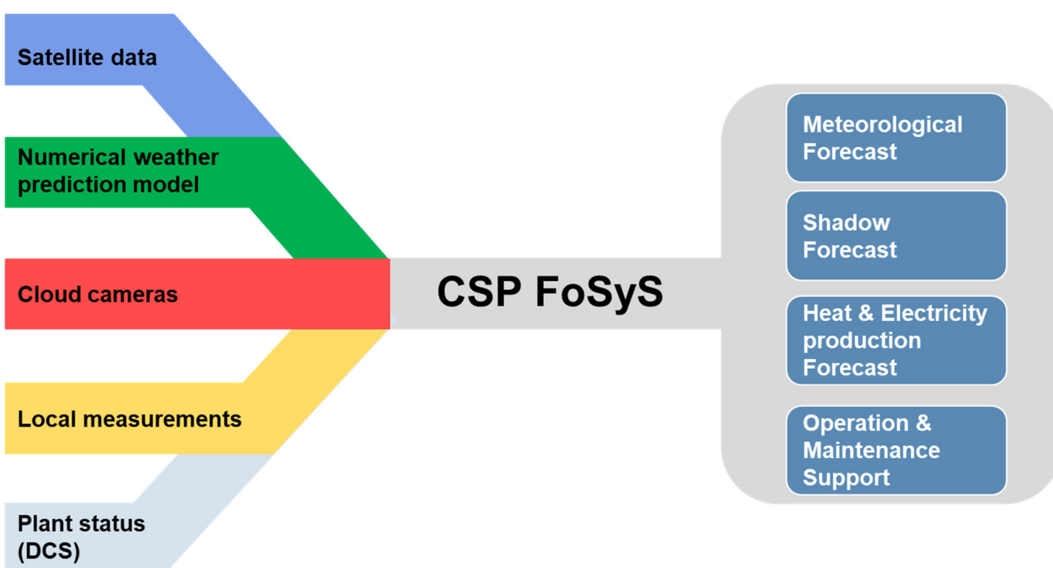

FIGURE 1. CSP FoSyS overview

SolarPACES 2019
AIP Conf. Proc. 2303, 160009-1–160009-9; https://doi.org/10.1063/5.0028950
Published by AIP Publishing. 978-0-7354-4037-1/$30.00

CLOUD AND AEROSOL MOTION BY SATELLITE

Cloud motion is monitored in near-real-time by three types of images. One image has a very high resolution in the visible solar spectrum, while a second image has a slightly lower resolution but shows natural colours by using additional infrared observations. The third image is based on infrared channels as well and allows especially the monitoring of strong aerosol events and the occurrence of cirrus clouds, which are both of special relevance to direct irradiance extinction.

A temporal slider allows playing movies forth and back at any speed the operator requests for a detailed assessment of the current meteorological situation.

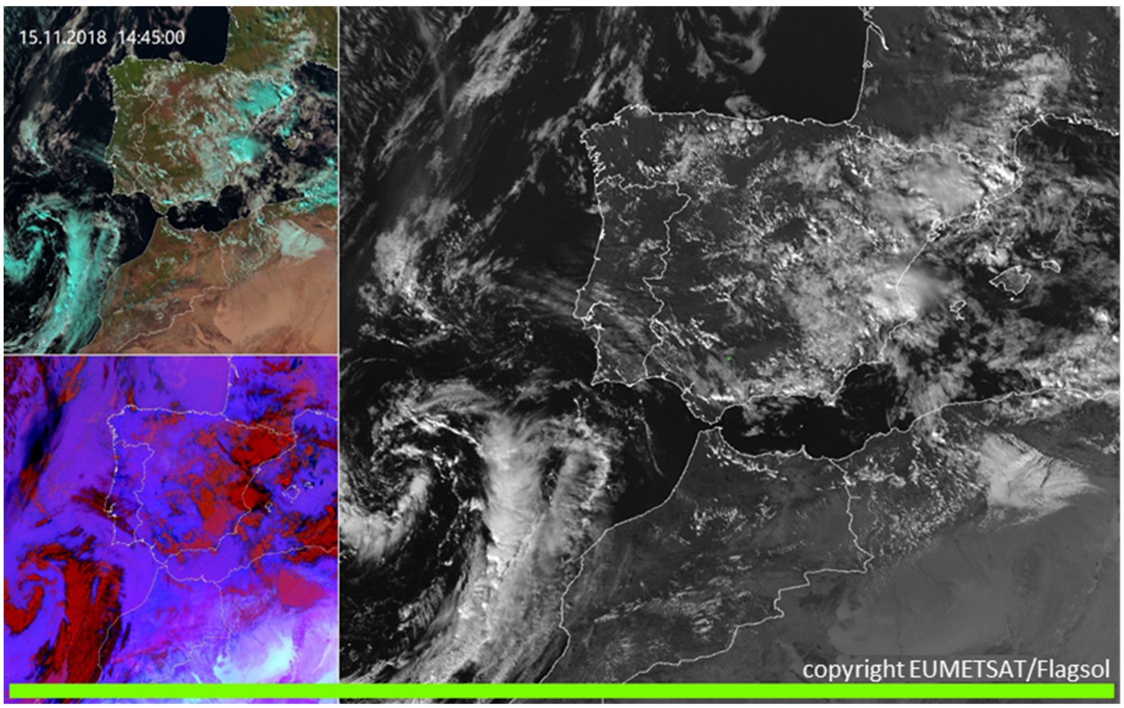

FIGURE 2. Cloud motion and aerosols by satellite based image sequences

The example below shows a case where a sand storm (shown in pink color) can be detected several hours before it reaches the solar power plant. Dust has a significant effect on DNI reduction and therefore significantly decreases the power produced by CSP power plants. Such information is very important in areas with high airborne dust aerosol concentration.

Additionally, the infrared image allows detecting cirrus clouds (dark red) very clearly, while they are hard to detect in the other channels.

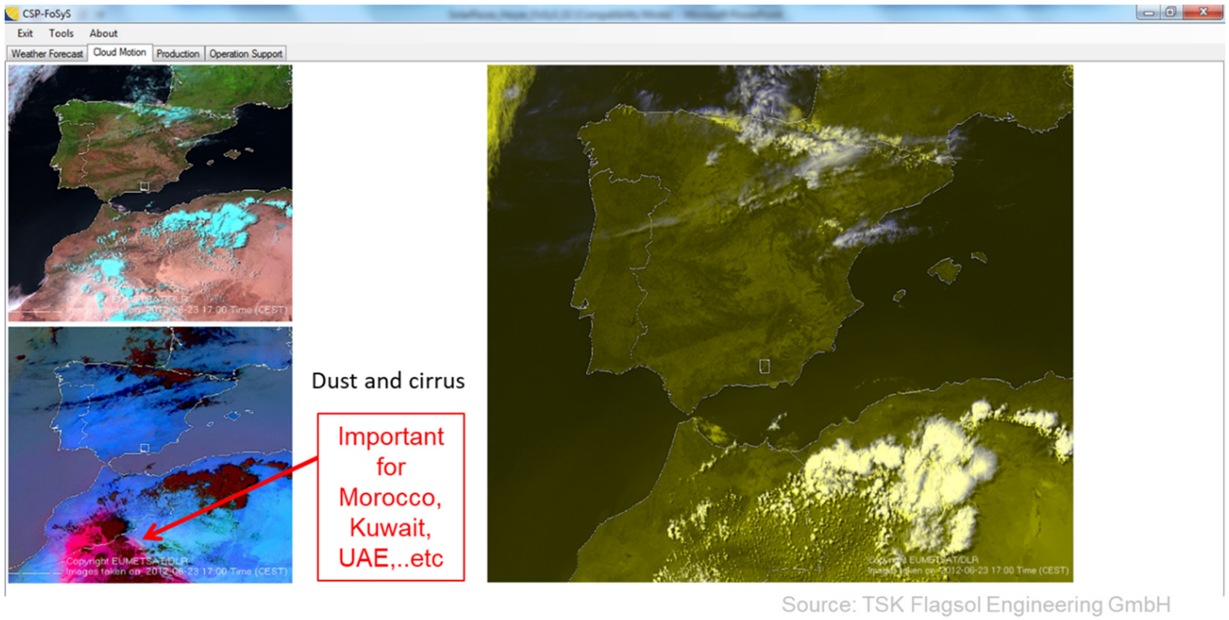

FIGURE 3. Example showing a sand storm originating in the Sahara and cirrus clouds over Spain. Satellite image copyright: EUMETSAT/Flagsol.

Thanks to the infrared observations, such information on aerosols and clouds is also available at nighttime and in the early morning during the plant start-up phase.

SATELLITE BASED DNI NOWCAST

The DNI nowcast algorithm is based on the use of a sequence of 3satellite images with a 15 minute time difference between the images. The location of clouds around the power plant is identified by multi-spectral cloud retrieval techniques in the visible and infrared range. According to the clouds' top temperature and infrared multispectral features of ice clouds, the clouds are classified into different layers (low, medium, high) and thin ice clouds are separated from optically thick clouds. Using a sequence of cloud masks, motion vectors of the clouds can be identified. Only louds coming towards the power plant are monitored and their optical depth is quantified. Based on cloud motion vectors for cloud edges, cloud speed is estimated and the arrival of clouds at the power plant is nowcasted. Based on the cloud optical depth, the extinction of radiation and therefore DNI is quantified. Furthermore, based on the spatial pixel to pixel variability a cloud optical depth (COD) percentile is derived – which is converted to DNI percentiles (P10, P50, and P90) in a radiative transfer scheme [2]. The DNI nowcast algorithm provides 1-minute temporally resolved nowcasts up to seven hours. The nowcast is updated every 15 minutes. The algorithm was previously described in [1,2] and is therefore only summarized here.

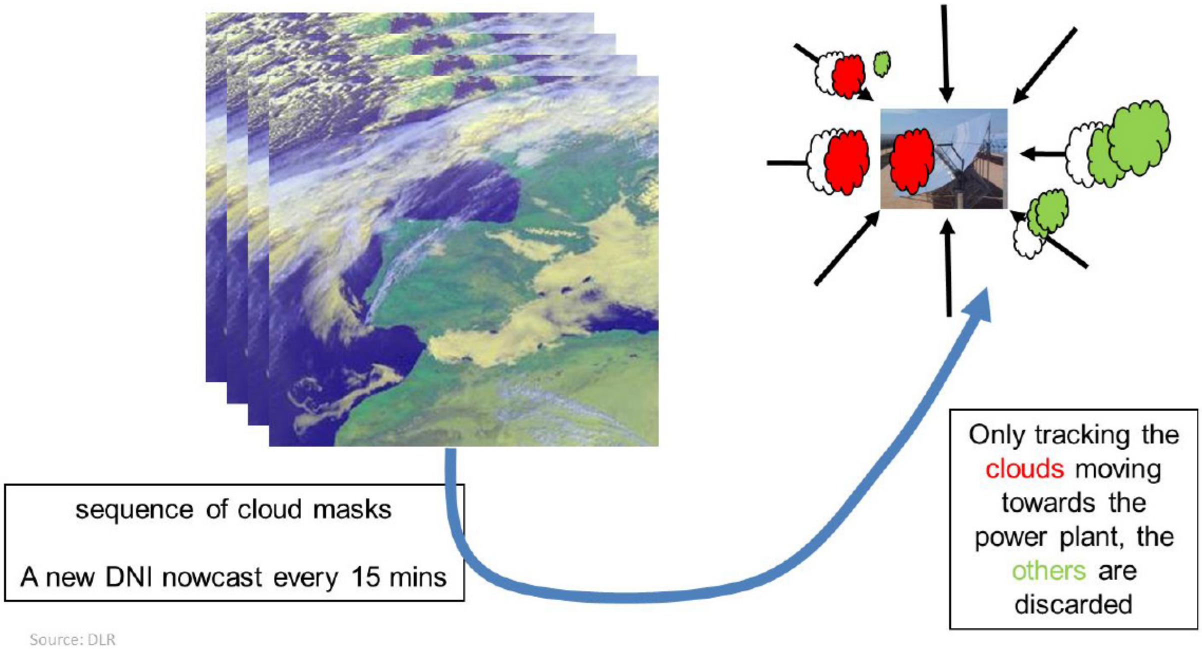

FIGURE 4. Satellite based DNI nowcast

The figure below is an example of the DNI nowcast as installed in La Africana CSP plant in the south of Spain. It can be seen that 3.5 hours after the nowcast (at 13:45h) clear-sky clouds will impact the operation of the plant.

The right half of FIGURE 5 shows the result compared to the ground measurement of DNI as obtained later by the meteo station in the power plant area. CSP power plants are generally equipped with ground measurements to measure meteorological parameters as DNI, wind speed, wind direction, ambient temperature, etc. It is obvious that there is a high degree of agreement with the nowcast.

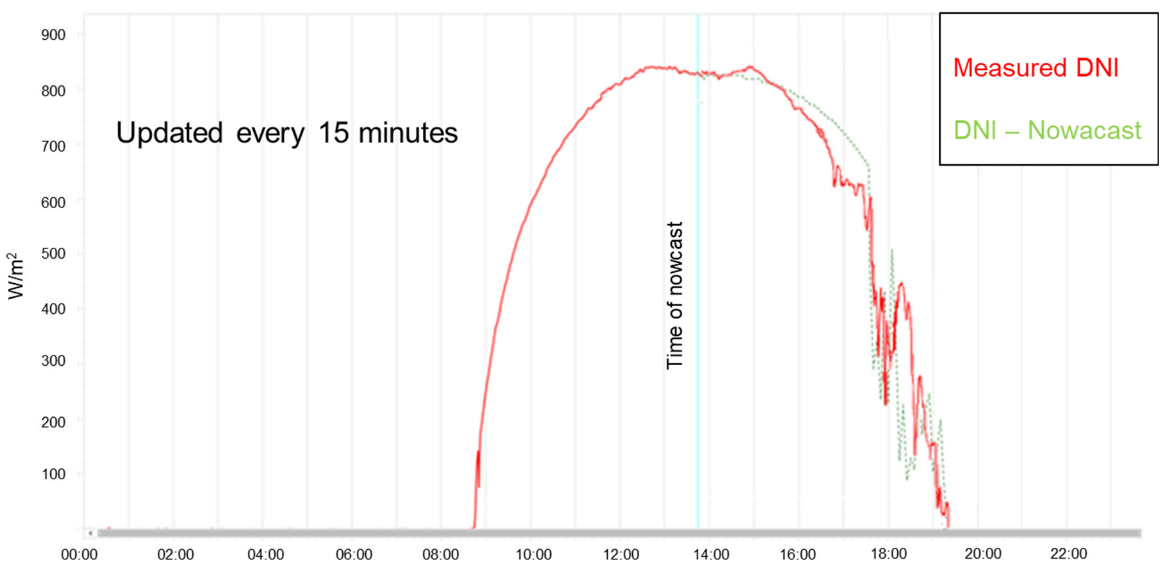

FIGURE 5. DNI nowcast result example

The spatial distribution of cloud optical depth from the sector the cloud is coming towards the power plant is used as an ensemble to predict the expected range of cloud optical depth and therefore the range of expected DNI, which is used in the merger concept.

LONG-TERM DNI FORECAST

The system also provides long-term meteorological and production forecasts based on numerical weather prediction (NWP) models. Probabilistic irradiance forecast data is provided by the Ensemble Prediction System (EPS) as operated routinely by the European Centre for Medium-Range Weather Forecasts (ECMWF). Forecasts are then post-processed from three hours accumulated energy to a 30 minutes average DNI prediction using a constant ratio of forecasted vs. clear sky curves. This DNI prediction is used to perform the day-ahead prediction of the power plant, e.g. as a basis for maintenance planning. This forecast provides also the uncertainty that covers the predicated range of radiation.

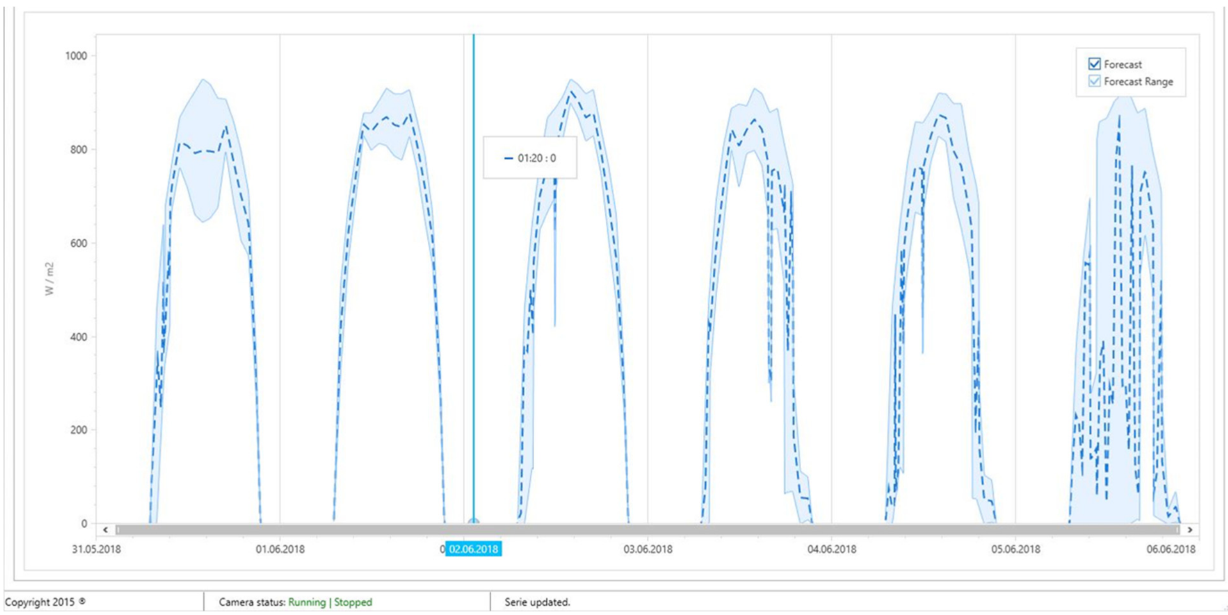

FIGURE 6. DNI forecast based on NWP probabilistic numerical weather prediction

For participation in the day-ahead electricity market, the user receives an email each day at 10:00 (Spanish time) which includes the DNI prediction of the next day (D+1).

ELECTRICITY AND HEAT FORECAST

CSP-FoSyS includes a power plant model, which is programmed to simulate the given plant's performance and calculate the estimated electrical power produced by the plant. The system has a connection to the power plant's distributed control system (DCS) to read some signals as e.g. mass flow rates, temperatures, storage tanks level, etc. This allows the system to simulate the current status of the plant before performing the power forecast. The meteorological forecast is used as input to the power plant model.

This power prediction sub-system creates a file, which includes the expected hourly production of the power plant, this is the file which the power plant operator sends for the participation in the day-ahead and intra-day market.

CLOUD MOTION BY CLOUD CAMERA

The system is equipped additionally with a cloud camera. The camera provides the user with a live view of the cloud motion around the sun's position since a sun-tracking algorithm has been developed and integrated to the system. This camera provides the user a higher resolution view of the clouds in the close vicinity while the satellite images offer a relatively lower spatial resolution but over a large geographical region. Since the operators typically do not have a full view of the surroundings in all geographical directions from their control room in a power plant.

FIGURE 7. Cloud camera for cloud motion live view

SHADOW MAP BY CLOUD CAMERAS

TSK Flagsol GmbH, DLR and CSP Services cooperated within an R&D project (WobaS) funded by the German federal ministry for economic affairs and energy (BMWi) to integrate a full cloud camera system into CSP-FoSyS. In order to extend its capabilities by providing shadow maps, to monitor and forecast the shadow movement over the solar field for 15 minutes in advance. The added system consists of four fish-eye camera. Multiple sky images are taken and are communicated via wireless antennas as shown in FIGURE 8.

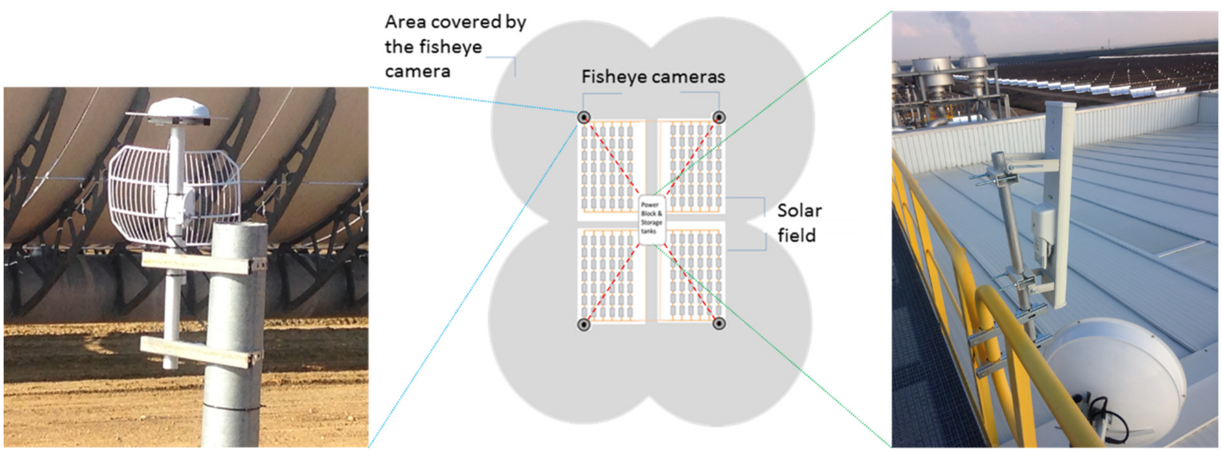

FIGURE 8. The camera system installation overview (middle), the fish-eye camera and directional antenna (left) and the receiving antenna installation (right)

The images are captured every 30 seconds by standard surveillance cameras (Mobotix Q24/Q25) and transmitted by antennas to the receiving antennas on the rooftop of the control building of the power plant. The images are taken from four spatially distributed cameras. These images are then processed by an algorithm, which is based on voxel carving. The images taken from different viewpoints allows computing a 3D shape of the cloud. In addition to tracking each object separately (multilayer cloud movements) [3].

The algorithm uses a four-dimensional clear sky library (CSL), in which an optically cloudy pixel is distinguished from an optically clear sky pixel. This four dimensional CSL method associates the Red-to-Blue Ratio RBR values for every pixel to the sun-pixel angle and pixel-zenith angle and additionally to the air mass and the DNI derived Linke turbidity [3].

The system provides two shadow-maps outputs as shown FIGURE 9, the image on the left shows the current shadow location on the solar field, one the right side a movie consists of several shadow images shows the shadow motion forecast for the next 15 minutes. The shadow map has a spatial resolution of 25 m² and a total edge length of 8 km.

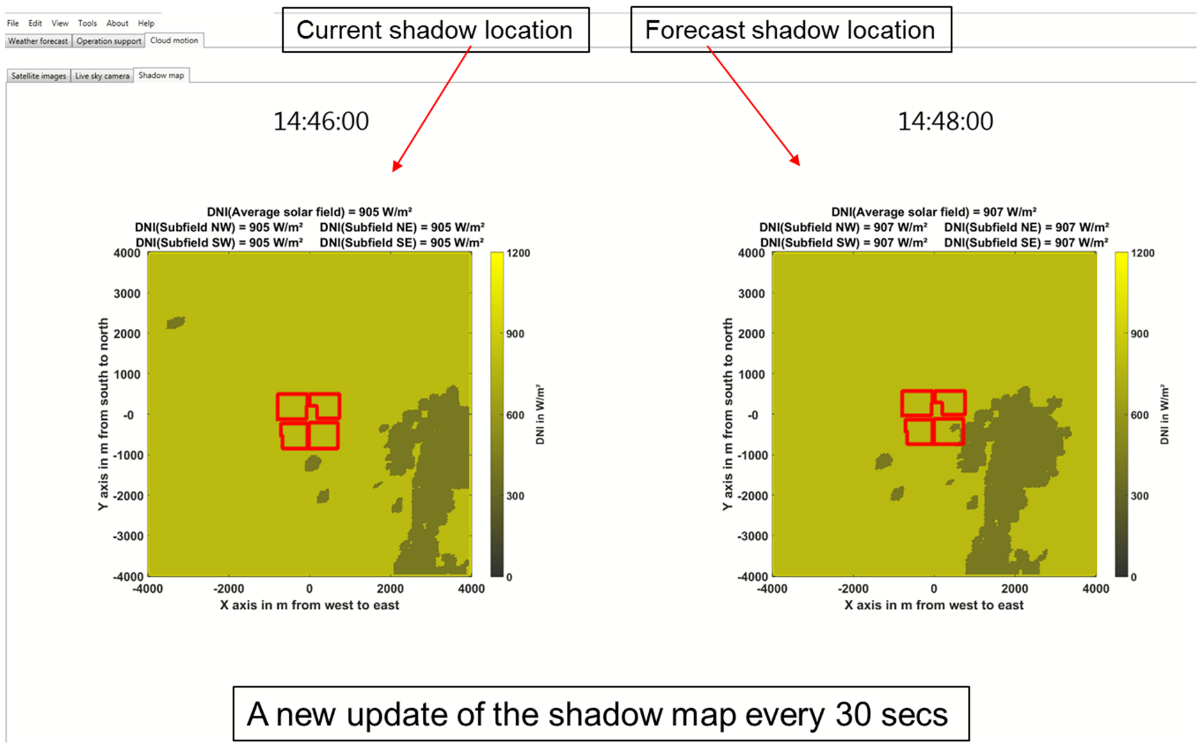

FIGURE 9. Shadow map of the current time (left) and a shadow motion forecast movie (right)

THE MERGER

A nowcast merger concept is developed to use these different DNI information and their probability percentiles in addition to the ground measurements to provide the user with the final DNI nowcast. Not only the last (newest nowcast) is used as an input to the merger but several previous nowcasts are used as well. For some cases the DNI nowcast shows a jumpiness behavior (high variable results) from one nowcast to the next, including its percentile range, this was used as a good indicator to the real 1 minute high variability DNI cases. It is known that the actual 1-minute values and their real variability in cloud conditions are out of reach of the satellite-based nowcasting [2]. However, it turns out that this jumpiness of nowcasts can be used as an additional information to the merger providing additional information on the actual cloud behavior.

A similar approach is applied on the use of several previous NWP data, with different generation time and not only the newest data. The concept is to find a trend of the predicted NWP DNI. On the other hand, this merger concept includes as well the power plant's own ground-based DNI measurements as an input, for post-processing the nowcast, by including information about aerosols. The ground measurements are used as an indication on the current aerosols concentrations.

The result of the development of the merger concept for another, more cloudy day (highly variable case) can be seen in FIGURE 10.

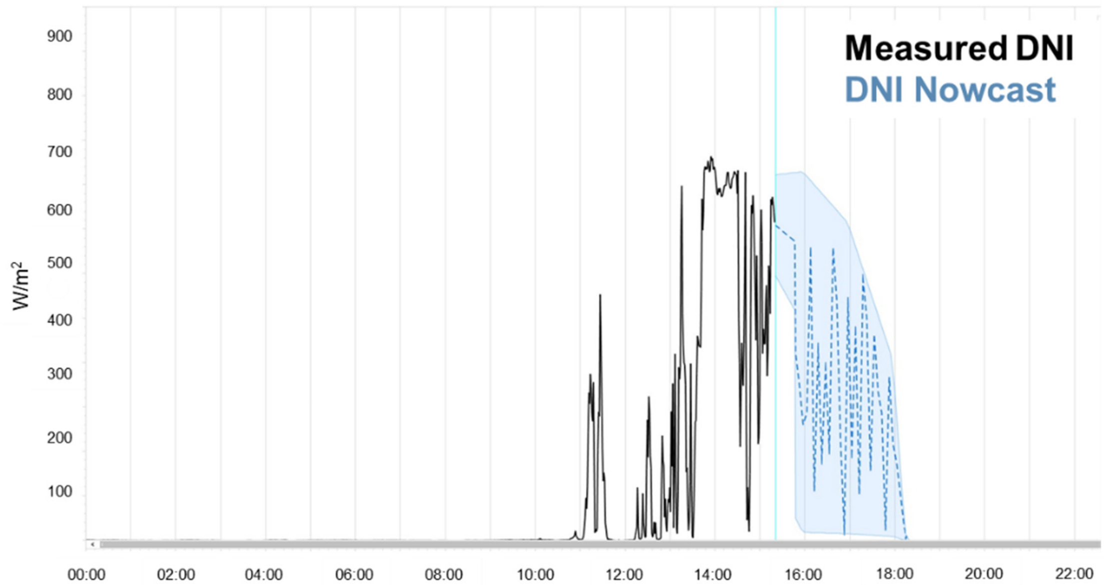

FIGURE 10. The Merger: DNI nowcast (high variability case)

It is well known that in highly variable atmospheric conditions the DNI values show chaotic characteristic. Such situations are now detected automatically, and the system then provides both a typical DNI nowcast (P50) showing such a temporal variability in a five minutes temporal resolution and DNI percentiles as an estimate of the expected radiation range (P10 to P90).

CONCLUSION

At the end of the projects, a meteorological and power forecast system was developed that provide the users with a complete range of forecast. A cloud motion monitoring system, a DNI nowcast based on satellite images and NWP, an innovative merger concept that uses different sources of DNI information, in addition to a power prediction based on a plant model and a shadow-map system.

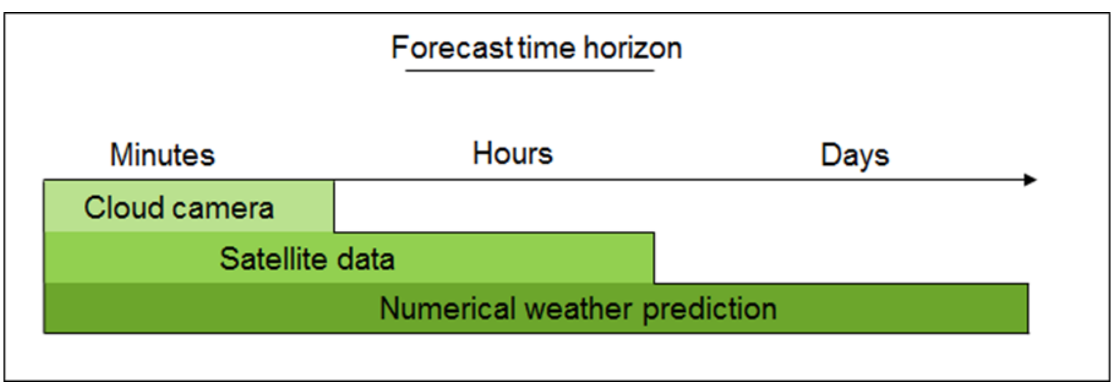

FIGURE 11. Forecast time horizon

CSP FoSyS was successfully installed and tested in a commercial CSP power plant. Positive feedback from the operators and shift leaders of the plant was received during the demonstration phase. The system was fully developed during the project phase and is currently ready to the market.

After the successful use in the CSP sector, the system is currently being extended for photovoltaic (PV) application through a new research and development project, to cover the entire solar sector applications (CSP and PV) and for the application of CSP-PV hybrid power plants as well.CSP-FoSyS will be installed soon in a hybrid CSP-PV plant.

ACKNOWLEDGMENTS

The system presented in this paper has received funding from the European Space Agency (ESA) within the CSP-FoSyS project and from the German Federal Ministry of Economics and Energy (BMWi) within the WobaS project. The authors would also like to thank the La Africana CSP plant for the support during installation and testing of the system.

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